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An ADP Proposal To Study The Formation and Evolution of Dust-Embedded Clusters

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Summary

Using high resolution and high sensitivity IRAS data at 12 and 25 μm, we have embarked on studies of low mass stars which have recently formed in the Ophiuchus, Corona Australis, and IC1396 dark clouds. The goals of these studies and our analysis procedure are outlined in Sections I and II. The successful application of these techniques to the Rho Ophiuchi infrared cluster is briefly described in Section III. The status of research performed under this grant is detailed in Section IV and summarized in Appendix A.

I. Goals of Study: Importance of IRAS Data

Young stellar objects (YSOs) embedded in molecular clouds have significant amounts of their energy absorbed by circumstellar dust and re-radiated in the 12-100 μm spectral region. Therefore, measuring the far-infrared luminosity of a YSO is critical for reliably estimating its total luminosity. The far-infrared energy output of a YSO is also a key to its evolutionary state. The relative amount of far-infrared to near-infrared emission tells us in general about the relative distribution of circumstellar dust in a spherical envelope vs. a disk. A protostellar or Class I spectral energy distribution will be dominated by a far-infrared emitting dust envelope while a T Tauri-like or Class II energy distribution will be dominated by near-infrared emission from a reddened stellar photosphere and a circumstellar disk (Adams, Lada, and Shu 1987; Myers *et al.* 1987).

In addition to determining the luminosity and evolutionary status of individual YSOs, we are interested in these properties collectively within a region of star formation. The number of YSOs in a given volume of gas can give us insight into the end result of star formation. In the absence of massive stars, low mass stars appear to form continuously within molecular clouds and this process can ultimately lead to gravitationally bound stellar systems (Wilking and Lada 1985). The collection of spectral energy distributions reveals the relative number of YSOs in a given phase of evolution and this information can be used to estimate the duration of star formation in the cloud (Wilking, Lada, and Young 1989). In addition, the characteristic time scales for each identifiable phase of pre-main-sequence evolution can be estimated. The empirically determined luminosity function of a dust-embedded cluster yields clues to the mass function of recently formed stars. Once corrected for evolutionary effects, the luminosity function can be compared to that of visible open clusters which closely mimic that derived from field stars for $M > 3\ M_\odot$ (i.e., the Initial Mass Function or IMF, Scalo 1986). In particular, this comparison can test the idea that molecular clouds form stars sequentially in mass as suggested by optical studies of open clusters (e.g., Adams, Strom, and Strom 1983).

II. Analysis Procedure

We have used both high resolution IRAS Pointed Observations and IRAS coadded survey data to locate individual sources of far-infrared emission in nearby molecular clouds. In regions of low source density, these data are about three times more sensitive at 12 μm than the Point Source Catalog. We have found that by combining the 12 and 25 μm band maps with existing higher resolution optical and near-infrared observations of the area of interest, we can effectively reduce the confusion in the IRAS data. Flux densities are derived almost exclusively from ADDSCANS, which permit us to measure sizes of sources and resolve closely-spaced sources. The IRAS data is used to target areas of the molecular cloud for new near-infrared observations, resulting in the most complete census of association members. Synthesizing the optical/near-infrared data with the IRAS data allows us to construct the 1-100 μm spectral energy distribution for each YSO crucial to our study of young clusters.

This procedure has been successfully applied to the young cluster embedded in the nearby Rho Ophiuchi molecular cloud. The results of the analysis of the IRAS Pointed Observations and coadded survey data have been reported in Young, Lada, and Wilking (1986) and Wilking, Lada, and Young (1989) and are briefly summarized below.

III. The Rho Ophiuchi Infrared Cluster

Sixty-four point-like sources of 12 μm emission have been identified in the main cloud of the Ophiuchus molecular complex. At least forty-four of these IRAS sources are associated with YSOs embedded in the cloud. As a result of these data, a total of 78 YSOs are now known to be embedded in the cloud. The high density of YSOs relative to molecular gas suggests that a significant fraction of the cloud core is forming a bound stellar cluster.

Combining the IRAS data with ground-based photometry, energy distributions over the 1-100 μm spectral region could be constructed for about 50 objects. The nearly equal number of heavily obscured Class I sources to T Tauri-like sources suggests the duration of the embedded state is 1-4 x 10^5 years, implying a mass accretion rate of 2.5-10 x 10^{-6} $M_\odot$/year for a 1 $M_\odot$ star. Limits to the number of post T Tauri stars in the clouds sets an upper limit of 3.5 x 10^6 years to age of this infrared cluster.

The luminosity function of the cluster shows that it contains primarily low-luminosity objects. Remarkably, the source luminosities are segregated by the shapes of their spectral energy distributions with the higher luminosity sources (5-50 $L_\odot$) displaying Class I spectral energy distributions. One explanation is that Class I sources have an additional source of luminosity (perhaps accretion) relative to their more evolved Class II counterparts. If this is true, then the Rho Oph infrared cluster is deficient in intermediate mass stars relative to the Initial Mass Function.

IV. Recent Results

A summary of publications and presentations related to research performed under this grant is given in Appendix A. This research activity has been directed toward two projects: (1) to extend our study of low-luminosity infrared clusters to the L1689 cloud (in the Ophiuchus complex) and the R Coronae Australis cloud and (2) to study star formation in bright-rimmed globules which comprise the IC1396 molecular complex. A brief description of each project will be given below.

IRAS coadded survey data and high resolution Pointed Observations have been analysed for both the L1689 and R Cr A clouds. In R Cr A, we have compiled a list of sixty-two 12 μm sources over a 40 pc^2 area of the complex. This is almost identical to the number studied in Rho Oph but over an area ten times larger. Fourteen of the sources have $S_\nu(12\ \mu m) < S_\nu(25\ \mu m)$: three of these are associated with reflection nebulosity excited by visible stars of spectral type B8-A5, seven are associated with T Tauri-like objects, and only four are associated with deeply-embedded Class I sources. The remaining 48 IRAS sources have $S_\nu(12\ \mu m) > S_\nu(25\ \mu m)$; the majority of these are associated with bright visible stars in the field. Hence the low ratio of Class I to Class II objects in R Cr A much more closely resembles that established for the Taurus-Auriga cloud (Kenyon *et al.* 1990) than the ratio near unity found in the Rho Oph core. Supporting ground-based infrared photometry was obtained in the summers of 1989 and 1990 at CTIO and the IRTF using infrared array cameras. The completion of the reduction of these data is necessary before spectral energy distributions of the R Cr A and L1689 YSOs can be made.

In the IC1396 region, we have analysed IRAS data to locate YSO candidates in the bright-rimmed clouds which ring this giant HII region. Fifteen sources were found coincident with dark cloud material, displaying bolometric luminosities of 30-700 $L_\odot$. External heating of the dust by the HII region has been assessed and found significant in more than half the sources. Most of the remaining objects appear to be deeply embedded YSOs in an early stage of evolution while two have colors indicative of T Tauri stars. Therefore, at the distance of 750 pc, there is a population of stars with $M < 5\ M_\odot$ forming in these globules and dark clouds. An additional 24 IRAS sources, further removed from the HII region, were also investigated and many of these appear to be intrinsic luminosity sources and YSO candidates.

References

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APPENDIX A

Research Activity Related to NAG NASA 5-1157

June 1989 - August 1990

I. Publications

"Star Formation in the Ophiuchus Molecular Cloud Complex", to appear in *Star Formation in Southern Molecular Clouds*, ed. Bo Reipurth, 1990, in press.

"A Search for Embedded Young Stellar Objects In and Near the IC1396 Complex", with R. D. Schwartz and A. L. Gyulbudagian, *Astrophysical Journal*, 1990, in press.

"The Initial Stellar Population", with H. Zinnecker and M. McCaughrean, to appear in *Protostars and Planets III*, ed. E. Levy, 1990, in press.

"IRAS Observations of the R Coronae Australis Infrared Cluster", with C. J. Lada, E. T. Young, T. P. Greene, and M. R. Meyer, in preparation.

II. Presentations

A. Oral presentations

"The Rho Ophiuchi Infrared Cluster", July 20, 1989, Cerro-Tololo Inter American Observatory, La Serena, Chile.

B. Poster presentations

"Star Formation in the Ophiuchus Molecular Complex", July 20, 1989, ESO Workshop on Low Mass Star Formation, Munich, West Germany.

"IRAS Observations of the R Coronae Australis Infrared Cluster", May 28 - June 8, 1990, NATO-ASI Workshop on Star Formation, Heraklion, Crete.